

# New Gauge Bosons from String Models\*

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## Abstract

We address the mass ranges of new neutral gauge bosons and constraints on the accompanying exotic particles as predicted by a class of superstring models. Under certain assumptions about the supersymmetry breaking parameters we show that breaking of an additional  $U(1)'$  symmetry is radiative when the appropriate Yukawa couplings of exotic particles are of order one, analogous to the radiative breaking of the electro-weak symmetry in the supersymmetric standard model due to the large top-quark Yukawa coupling. Such large Yukawa couplings occur for a large class of string models. The  $Z'$  and exotic masses are either of  $\mathcal{O}(M_Z)$ , or of a scale intermediate between the string and electro-weak scales. In the former case,  $M_{Z'} = \mathcal{O}(1 \text{ TeV})$  may be achievable without excessive fine tuning, and is within future experimental reach.

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\*This paper is a summary, with a more phenomenological emphasis and additional discussion, of the results in our earlier article *Implications of Abelian Extended Gauge Structures from String Models*, hep-ph/9511378.

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## I. INTRODUCTION

New neutral gauge bosons  $Z'$  are a feature of many models addressing the physics beyond the standard model (SM). The phenomenology of possible heavy gauge bosons has been extensively studied in the past. There are stringent limits on their mass and mixings from precision electro-weak experiments [1,2] and from direct searches [3]. The existence of a  $Z'$  affects precision electro-weak data (a) because  $Z - Z'$  mixing pushes the  $Z$  mass below the standard model expectation; (b) this expectation is itself modified by mixing, because it depends on the weak angle, the value of which is confused or distorted by the effects of mixing on other observables. (c) Both the mixing and the heavy particle exchange lead as well to other changes in the predictions for the various observables, implying new terms in the effective interactions relevant to each process and leading to different apparent values of the weak angle determined in different processes. Thus, the limits from precision experiments vary significantly from model to model because of the different chiral couplings to the ordinary fermions. Typically, the mass of a heavy  $Z'$  must exceed  $\sim 400$  GeV and the  $Z - Z'$  mixing angle must be smaller than a few times  $10^{-3}$  in those models in which the  $Z'$  couples significantly to charged leptons, including the standard examples from grand unification [1]. Models with suppressed couplings to charged leptons can tolerate much larger mixings (several percent), with the dominant constraint coming from the shift in the light  $Z$  mass, as is described in the Appendix. Such models may be motivated [4] by the possible enhancement in  $Z \rightarrow b\bar{b}$  decays suggested by the LEP data [5]. The direct production limits [3] are likewise very sensitive to the  $Z'$  couplings as well as to the number of open channels for the decays (*e.g.*, into exotic particles or superpartners), but are again typically in the 300-600 GeV range for grand unification type models.

The identification and diagnostic study of heavy gauge bosons at future colliders has been investigated in detail [6]. It should be possible to discover a heavy  $Z'$  with mass up to  $\sim 5$  TeV through its leptonic decay channels,  $pp \rightarrow Z' \rightarrow \ell^+\ell^-$ ,  $\ell = e$  or  $\mu$ , at the LHC, while  $\gamma - Z - Z'$  interference effects should be observable at a 600 GeV  $e^+e^-$  collider (NLC) for  $M_{Z'}$  up to  $\sim 2$  TeV. If such a  $Z'$  exists, it should be possible to obtain useful diagnostics about its coupling by forward-backward asymmetries, rapidity distributions, rare decays such as  $Z' \rightarrow W\ell\nu$ , and associated productions with a  $Z$ ,  $W$ , or  $\gamma$ , for masses up to  $\sim 3$  TeV at the LHC, with the LHC and NLC providing complementary information. (For a review see Ref. [6] and references therein.)

There have also been studies of the present and future constraints on possible exotic particles, such as heavy non-sequential quarks, leptons, or standard model singlets [7]. For example, some models predict the existence of a heavy,  $SU(2)_L$ -singlet, charge  $-1/3$  quark,  $D_L - D_R$ , which could be produced at a hadron collider by ordinary QCD processes and decay by  $D_L - b_L, s_L, d_L$  mixing into, *e.g.*,  $cW$ ,  $bZ$ , or  $bH$ , where  $H$  is a neutral Higgs boson. Typically, the  $cW$ ,  $bZ$ , and  $bH$  decays occur in the ratio  $\simeq 2 : 1 : 1$ . Currently,  $m_D > 85$  GeV if it mixes mainly with  $b$  [7]. Additionally, precision experiments (weak charged current, neutral current, and flavor changing constraints) typically imply<sup>1</sup> that the mixing

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<sup>1</sup>Heavy gauge bosons and exotic matter constraints have been addressed together in [8].

between  $D_L$  and  $d_L$  is less than  $\sim 0.01$  [7]. Similarly, some models imply the existence of new  $SU(2)_L$ -doublets of leptons,  $\begin{pmatrix} E^+ \\ E^0 \end{pmatrix}_L$  and  $\begin{pmatrix} E^+ \\ E^0 \end{pmatrix}_R$ , which can be produced by ordinary electro-weak processes, with the lightest decaying by mixing with ordinary leptons. In both examples, the exotic particles are vector, *i.e.*, both the  $L$  and  $R$  fields have the same standard model transformation properties. Vector particles could actually have bare masses as far as the standard model is concerned, but in most theories there are additional symmetries which forbid these and require that the masses be generated by some form of spontaneous symmetry breaking. New vector multiplets (or supermultiplets) could in principle have arbitrarily large masses since they do not require  $SU(2)_L \times U(1)$  breaking, and they are the most commonly predicted new type of matter in many standard model extensions.

In models with extended gauge symmetry, but which do not incorporate constraints of such underlying dynamics as grand unification, supersymmetry, supergravity, or string theory, the mass and couplings of additional gauge bosons are free parameters, and thus their masses can be anywhere from about 1 TeV to the Planck scale  $M_{Planck}$ . In addition, the masses and couplings of the additional exotic particles which usually accompany the  $Z'$  are also free parameters. Thus, such models lack a unique predictive power for  $Z'$  physics at future experiments.

The situation is different for models that incorporate constraints of supersymmetry: supergravity theories and, in particular, those that are predicted from string theory. String theory models necessarily include gravitational interactions (as a consistent part of the theory), and supersymmetry is restored at sufficiently large energy scales. In addition, for each of the models the light particle spectrum as well as their couplings are calculable, thus providing a major advantage over models in which both the particle content and the couplings are put in the theory by hand.

Unfortunately, there are two major hurdles that prevent one from obtaining unique low energy predictions of string theory: (i) by now a very large number of string models have been constructed, and one does not have a first principle guidance to single one model over another; (ii) while these models possess supersymmetry at large energy scales, one does not presently know how to break supersymmetry without introducing new parameters. Both problems are believed to have an ultimate resolution in the non-perturbative string dynamics.

In spite of the above unsolved problems one can take a less ambitious attitude and consider only those string models which have a potential to be realistic. Those are string models with supersymmetry, the standard model (SM) gauge group as a part of the gauge structure, and a particle content that includes three SM families [9–11] and at least two SM Higgs doublets, *i.e.*, the string vacua which have at least the ingredients of the MSSM. A number of such string models have been constructed [10,12–14]. Also, one may parameterize our ignorance of supersymmetry breaking by introducing supersymmetry breaking mass and trilinear interaction terms. The mass terms ultimately drive the electro-weak symmetry breaking, and thus are of the order of the electro-weak scale. The models which have been constructed often contain additional  $U(1)'$  symmetries and additional exotic matter multiplets.

A class of string models with the features mentioned above and an additional  $U(1)'$

symmetry provide a testing ground to address the following phenomenological issues: (i) a scenario, which specifies the scale of  $Z'$  and (ii) the mass and phenomenological implications of the exotic particles accompanying the new gauge boson. We have identified several distinct scenarios, each of which can be illustrated by a specific string model.

A main conclusion is that a large class of string models not only predict the existence of additional gauge bosons, but often imply the masses of the new gauge bosons and the exotic particles which necessarily accompany them to be in the electro-weak range. Each specific model leads to calculable predictions (which, however, depend on the assumed supersymmetry breaking mass terms) for the masses, couplings, and mixing with the  $Z$  of the new boson(s), as well as for the masses and quantum numbers of the associated exotic matter. We would thus like to advocate that, from the string point of view, new gauge bosons and associated exotic matter are perhaps the next best motivated new physics – after the Higgs and supersymmetric particles – to be searched for at future experiments.

The paper is organized as follows. In Section 2 we specify in more detail the features of the string models and their advantage over SM physics. In Section 3 we give the specific scenarios for the  $Z'$  masses achievable without excessive fine-tuning of the supersymmetry breaking parameters and constraints on exotic particles accompanying the new gauge boson(s). We show examples in which the additional  $Z'$  mass is: (a) comparable to that of the  $Z$  (already excluded); (b) in the 300 GeV to 1 TeV range, which may still be barely allowed but easily within the range of future or present colliders; (c) at an intermediate scale (*e.g.*,  $10^8 - 10^{14}$  GeV). It is argued that in case (b) it is difficult though not impossible to satisfy existing constraints on  $Z - Z'$  mixing, especially for lower values of  $M_{Z'}$ , and that  $Z'$  masses above 1 TeV are not expected (given our assumptions) without excessive fine tuning. Conclusions are given in Section 4. The Appendix discusses the limits on  $Z - Z'$  mixing.

The results presented in this paper provide a summary of Ref. [15], but with a more phenomenological emphasis. The more detailed version [15] also provides additional technical details and illustrations of the scenarios within specific string models.

## II. FEATURES OF STRING MODELS

Let us first specify the generic features of supersymmetric string models with the standard model (SM) gauge group  $SU(2)_L \times U(1)_Y \times SU(3)_C$ , three ordinary families, and at least two SM doublets, *i.e.*, a set of models with at least a particle content of the minimal supersymmetric standard model (MSSM). In addition, from a set of models we select only those with  $SU(3)_C$ ,  $SU(2)_L$  and  $U(1)_Y$  all embedded into the  $SU(5)$  gauge group, since for other types of embedding the normalization of the  $U(1)_Y$  gauge group coupling is different from the one leading to the gauge coupling unification in the MSSM model.

In general these models also contain a set of particles which are singlets of the SM gauge group, but which transform non-trivially under an additional non-Abelian “shadow” sector group, and a number of additional  $U(1)$ ’s, one of them usually anomalous. The shadow sector non-Abelian gauge group may play a role in dynamical supersymmetry breaking. In addition, there are typically a large number of additional matter multiplets, which transform non-trivially under  $U(1)$ ’s and/or the standard model symmetry. In general such models also lead to fractionally charged color singlets, which may have important phenomenological

[16] consequences.

The anomalous  $U(1)$  group of such models is broken at  $M_{string}$  [17–19] by nonzero vacuum expectation values (VEV's) of certain multiplets which preserve supersymmetry and consistency of the theory at the loop level of string theory. At the same time, this mechanism ensures that a number of additional non-anomalous  $U(1)$ 's are broken and a number of additional multiplets become massive. Thus, the enhanced gauge symmetry and the exotic particle content is in general drastically reduced. Nevertheless, there are often one or more non-anomalous  $U(1)$ 's and associated exotic matter that are left unbroken. The physics associated with these left over non-anomalous  $U(1)'$  symmetries is the subject of this paper.

One should, however, point out that the models discussed in general may not be consistent with all of the phenomenological constraints: (i) the models could have additional color triplets in the spectrum which could mediate a too fast proton-decay [20,21], (ii) the detailed mass spectrum of the ordinary fermions [9,11] may not be realistic, (iii) a scenario for the symmetry breaking of additional  $U(1)$ 's may not be consistent with phenomenological constraints on the exotic multiplets, such as gauge coupling unification [22]. In addition, it is not clear how to implement the supersymmetry breaking scenario; we parameterize it by introducing supersymmetry breaking mass and cubic terms.

### III. $U(1)'$ SYMMETRY BREAKING SCENARIOS

Within the models discussed in the previous Section the pattern of additional  $U(1)'$  symmetry breaking is very constraining. First, the models possess supersymmetry, which relates the interactions of integer (boson) and half-integer (fermion) spin particles, *i.e.*, those between the particle and its superpartner; second, the type of particles and their couplings are calculable. With the assumptions that supersymmetry is parameterized by supersymmetry breaking mass parameters (and cubic scalar interactions), and that dynamical effects in the shadow sector do not break the  $U(1)'$  symmetry, the  $U(1)'$  symmetry breaking must take place via the Higgs mechanism, *i.e.*, by giving non-zero vacuum expectation values (VEV) to spin-zero particles  $S_i$ , which are singlets<sup>2</sup> under the SM symmetry, but carry non-zero charges under the  $U(1)'$ . Non-zero VEV's of  $S_i$  therefore preserve the SM gauge symmetry; however, they yield a mass term for  $Z'$ , which is of the order of the VEV's of  $S_i$ . The analogous Higgs mechanism for spontaneous symmetry breaking (SSB) of the electro-weak symmetry takes place when the  $SU(2)_L$  doublet(s) acquire nonzero VEV('s), giving mass to the  $Z$  and  $W^\pm$  gauge bosons.

We assume that the soft supersymmetry breaking mass-square terms for the scalar fields are positive at  $M_{string} \sim 10^{17} - 10^{18}$  GeV and of the order of gravitino mass  $m_{3/2}$ , which is assumed to be of  $\mathcal{O}(1)$  TeV. The appearance of positive mass-square terms at  $M_{string}$  is the case in almost all models that have been explored. Then the only way of achieving SSB is via a radiative mechanism. Namely, since such SM singlets have positive (supersymmetry breaking) mass-square terms at large energies, these terms need to be driven negative at

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<sup>2</sup>The possibility of breaking the  $U(1)'$  symmetry by the VEV's of Higgs doublets is discussed in [15]. In that case, it is difficult to achieve a hierarchy between the  $Z'$  mass and the ( $W$ ,  $Z$ ) masses.

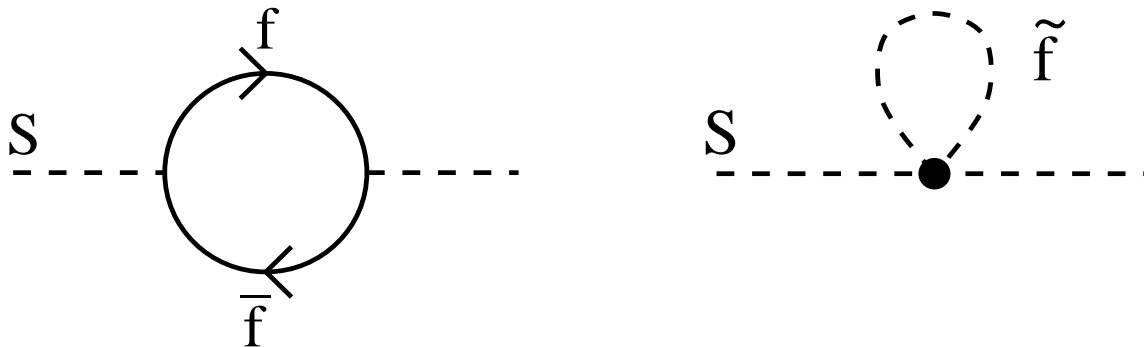


FIG. 1. Loop corrections which lead to the running of the mass-square term for the scalar  $S$ .  $f$  and  $\tilde{f}$  denote the fermion(s) and their supersymmetric partner(s), respectively.

lower energies to ensure a global minimum of their potential with nonzero VEV's for such fields.

The magnitude of the couplings and mass parameters depends on the energy scale at which they are measured. The renormalization group equations account for the loop-corrections to the physical couplings and mass parameters, and track the dependence of these couplings on the energy scale. In particular, some supersymmetry breaking mass-square parameters of the Higgs field(s)  $S_i$  can become negative if  $S_i$  have a large Yukawa coupling (of  $\mathcal{O}(1)$ ) to fermions with appropriate representations under the SM gauge group, *e.g.*, SM doublets or triplets. In this case the loop corrections due to such Yukawa couplings (see Fig.1) contribute to the renormalization group equations for the running of the mass-square terms in such a way that the mass-square term for  $S_i$  can be driven negative, while that for the supersymmetric partners of the fermions (that couple to  $S_i$  via the Yukawa couplings) remain positive (see Fig. 2).<sup>3 4</sup> Thus, the scale of  $U(1)'$  symmetry breaking depends on both the type of SM singlets  $S_i$  responsible for the  $U(1)'$  symmetry breaking and on the Yukawa couplings of such multiplet(s) to other exotic particles.

One of the features which distinguishes string models from the generic MSSM is that the Yukawa couplings are calculable and thus are not free parameters. Interestingly, for the class of string models discussed in the the previous Section the corresponding Yukawa

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<sup>3</sup>For the explicit form of the renormalization group equations, applied to specific string models, see the appendix of Ref. [15]. For a detailed discussion of renormalization group equations within the MSSM see Ref. [23].

<sup>4</sup>An analogous scenario takes place in the radiative breaking of the electro-weak symmetry in the MSSM. There the positive (supersymmetry breaking) mass-square terms of the Higgs electro-weak doublet which couples to the top quark is driven to a negative value at low energies due to the large top-quark Yukawa coupling (which determines the mass of the top quark  $\sim 170$  GeV), while the mass-square terms for the stops (supersymmetric partner of the top quark) remain positive.

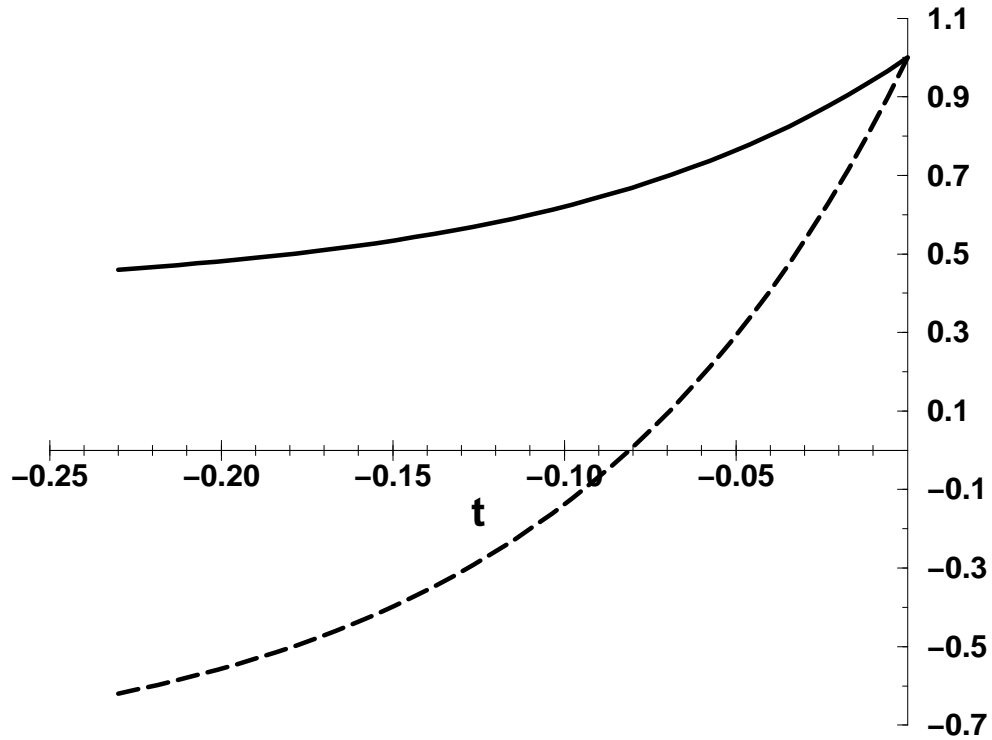


FIG. 2. The running of the scalar mass-square terms (in units of  $m_{3/2}^2$ ) for a singlet field  $S$  (dashes) coupled to a pair of  $SU(3)$  triplets  $D$  (solid line) (example 2 from the appendix to [15]).  $t$ , defined as  $\log(\mu/M_{string})/16\pi^2$ , varies from  $-0.23$  at the electro-weak scale  $\mu = M_Z$  to  $0$  at the string scale  $\sim 5 \times 10^{17}$  GeV.

couplings are either of  $\mathcal{O}(g)$  ( $g$ -gauge coupling) or zero<sup>5</sup>. Thus, if the relevant coupling is non-zero it may be sufficiently large to ensure radiative breaking of the  $U(1)'$  symmetry.

For each of these possibilities the pattern of  $U(1)'$  symmetry breaking and the running of the gauge couplings still depend on the specific exotic particle content and their couplings. We shall now discuss the possible scenarios for observable sector  $U(1)'$  symmetry breaking. For the sake of simplicity we shall address scenarios in which the electro-weak symmetry is broken due to the non-zero VEV of the Higgs doublet that couples to the top-quark, *i.e.*, a large  $\tan\beta$  scenario of the MSSM. A generalization to scenarios that accommodate other ranges of  $\tan\beta$  is straightforward. We will emphasize the general features which hold in each scenario. However, we emphasize that in each specific model the  $Z'$  mass, mixing, and couplings, as well as the properties of the exotic matter, are in principle calculable, though in practice they depend on the details of the soft supersymmetry breaking.

### A. Symmetry Breaking Due to One $U(1)'$ Charged Standard Model Singlet

Suppose that the radiative breaking of  $U(1)'$  is due to one SM singlet  $S$ , that is charged under  $U(1)'$ . Namely, only one  $S$  has its effective mass-square driven to a negative value at low energies, thus allowing for a non-zero VEV. The  $Z - Z'$  mass-square matrix is then:

$$M_{Z-Z'}^2 = \begin{pmatrix} \frac{1}{2}G^2H^2 & Gg'Q'_H H^2 \\ Gg'Q'_H H^2 & 2g'^2(Q'^2_H H^2 + Q'^2_S S^2) \end{pmatrix}, \quad (1)$$

where  $H$  and  $S$  denote the VEV's for the SM Higgs doublet and singlet, respectively, and  $Q'_{H,S}$  are the corresponding  $U(1)'$  charges. Here  $G \equiv \sqrt{g^2 + g_Y^2}$ , where  $g, g_Y, g'$  are the gauge couplings at the SSB scale for  $SU(2)_L$ ,  $U(1)_Y$  and  $U(1)'$ , respectively.

The exotic matter to which  $S$  couples acquires a mass of order  $\mathcal{H}S$ , where  $\mathcal{H}$  is the relevant Yukawa coupling between the particular exotic matter and  $S$ . In general, there will be an additional soft supersymmetry breaking mass term contributing to the mass of the exotic matter even in the absence of the relevant Yukawa coupling(s).

The nature of the  $Z - Z'$  hierarchy now crucially depends on the allowed VEV's  $S$  and  $H$ , which are constrained by the form of the potential. At low energies the potential can be written for the particular direction with non-zero VEV's as:

$$V = -|m_H|^2 H^2 - |m_S|^2 S^2 + \frac{1}{8}G^2 H^4 + \frac{g'^2}{2}(Q'_H H^2 + Q'_S S^2)^2, \quad (2)$$

where we have extracted explicit minus signs from the negative mass-square terms. Note that due to the constraints of supersymmetry the quartic couplings in (2) are proportional to the gauge couplings and thus are *not* free parameters.

One encounters the following two scenarios:

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<sup>5</sup>The same is true for the Yukawa coupling of the ordinary families to the Higgs doublets.



- (i): The relative signs of  $Q'_H$  and  $Q'_S$  are opposite.

In this case the minimum of the potential (2) is for:

$$H^2 = \frac{4(|m_H|^2 + \frac{|Q'_H|}{|Q'_S|}|m_S|^2)}{G^2}, \quad S^2 = \frac{|m_S|^2}{|Q'_S|^2 g'^2} + \frac{|Q'_H| H^2}{|Q'_S|} \quad (3)$$

and the  $Z - Z'$  mass-square matrix is

$$M_{Z-Z'}^2 = 2 \begin{pmatrix} (|m_H|^2 + \frac{|Q'_H|}{|Q'_S|}|m_S|^2) & \frac{2g'Q'_H}{G}(|m_H|^2 + \frac{|Q'_H|}{|Q'_S|}|m_S|^2) \\ \frac{2g'Q'_H}{G}(|m_H|^2 + \frac{|Q'_H|}{|Q'_S|}|m_S|^2) & \frac{4g'^2 Q_H'^2}{G^2}(1 + \frac{|Q'_S|}{|Q'_H|})(|m_H|^2 + \frac{|Q'_H|}{|Q'_S|}|m_S|^2) + |m_S|^2 \end{pmatrix}. \quad (4)$$

It is difficult to achieve the needed hierarchy between  $M_Z$  and  $M_{Z'}$ , unless  $|Q'_S| \gg |Q'_H|$  and  $|m_S|^2 \gg |m_H|^2$ , in such a way that  $|Q'_H/Q'_S| = \mathcal{O}(|m_H|^2/|m_S|^2)$ . The first condition is not normally expected to hold, except in the limiting case  $Q'_H = 0$ .

- (ii): The relative signs of  $Q'_H$  and  $Q'_S$  are the same.

The minimum of the potential (2) now occurs for:

$$H^2 = \frac{4(|m_H|^2 - \frac{|Q'_H|}{|Q'_S|}|m_S|^2)}{G^2}, \quad S^2 = \frac{|m_S|^2}{|Q'_S|^2 g'^2} - \frac{|Q'_H| H^2}{|Q'_S|} \quad (5)$$

and the  $Z - Z'$  mass-square matrix becomes:

$$M_{Z-Z'}^2 = 2 \begin{pmatrix} (|m_H|^2 - \frac{|Q'_H|}{|Q'_S|}|m_S|^2) & \frac{2g'Q'_H}{G}(|m_H|^2 - \frac{|Q'_H|}{|Q'_S|}|m_S|^2) \\ \frac{2g'Q'_H}{G}(|m_H|^2 - \frac{|Q'_H|}{|Q'_S|}|m_S|^2) & \frac{4g'^2 Q_H'^2}{G^2}(1 - \frac{|Q'_S|}{|Q'_H|})(|m_H|^2 - \frac{|Q'_H|}{|Q'_S|}|m_S|^2) + |m_S|^2 \end{pmatrix}. \quad (6)$$

In this case one encounters an interesting possibility for achieving a hierarchy without an unusually small ratio of  $|Q'_H/Q'_S|$ , provided  $0 < |m_H|^2 - \frac{|Q'_H|}{|Q'_S|}|m_S|^2 \ll |m_S|^2$ . In this limit, the  $Z - Z'$  mixing angle is

$$\theta_{Z-Z'} \sim \frac{2g'Q'_H}{G} \frac{M_Z^2}{M_{Z'}^2}. \quad (7)$$

For small  $g'Q'_H/G$  the  $Z - Z'$  mixing could be sufficiently suppressed to be consistent with the experimental bounds for  $M'_Z \leq \mathcal{O}(1)$  TeV, as is further discussed in the Appendix.

One can illustrate [15] the above scenarios in a particular class of string models. The second case is of interest, because there a reasonable hierarchy can be achieved without fine tuning of the soft supersymmetry breaking parameters or choices of models with unusual values of  $|Q'_H/Q'_S|$ . *E.g.*, such models can provide for a hierarchy  $|m_H|^2 - |m_S|^2 |Q'_H|/|Q'_S| \ll$

$|m_S|^2$ , say,  $|m_H|^2 - |m_S|^2|Q'_H|/|Q'_S| \sim |m_S|^2/10$ . If, in addition, one has *e.g.*,  $g'|Q'_H|/G \sim 1/4$ , one obtains  $M_{Z'}^2 \sim 10M_Z^2$  and the mixing angle  $\theta_{Z-Z'} \sim 0.05$ . In this example,  $M_{Z'}$  is barely within the current experimental bounds, while  $\theta_{Z-Z'}$  is too large for most choices of  $Z'$  couplings [1,3]. Somewhat larger values of  $M_{Z'}$  and smaller values of  $g'|Q'_H|/G$  may be consistent with observations.<sup>6</sup> Thus, without excessive fine tuning of the soft supersymmetry breaking parameters, the prediction of  $M_{Z'}$  is within experimental reach of present or future colliders. However, when the experimental bounds on  $M_{Z'}$  exceed the 1 TeV region, this scenario *cannot* be implemented without excessive fine tuning of the soft supersymmetry breaking parameters or unusual choices of the  $U(1)'$  charge assignments.

## B. Symmetry Breaking Due to Mirror-like Pairs of $U(1)'$ Charged Standard Model Singlets

In this case, negative mass-square terms are induced for two (or more)  $U(1)'$  charged SM singlets  $S_{1,2}$ , whose  $Q'_{S_{1,2}}$  charges have opposite sign. It turns out that supersymmetry constraints for the potential ensure that the minimum of the potential is along the VEV direction  $Q'_{S_1}S_1^2 = -Q'_{S_2}S_2^2 \equiv S^2$  ( $D$ -flat direction). Along this direction the potential for  $S$  has no quartic terms; however, the mass square term depends on the energy scale  $\mu$  at which it is measured. Namely, one now has to include the renormalization group improved potential, which along the flat direction is of the form :

$$V = m_S^2(\mu = S)S^2 \quad (8)$$

Thus, the minimum occurs near the energy scale  $\mu_{\text{crit}}$  at which  $m_S^2$  turns negative. In the case of radiative breaking with Yukawa couplings of  $\mathcal{O}(1)$ , it turns out that  $m_S^2(\mu_{\text{crit}})$  is much larger than the soft supersymmetry breaking mass terms. For the models considered it is [15] typically four to ten orders of magnitude below  $M_{\text{string}}$ . Therefore, in the case of flat directions the scale of symmetry breaking, *i.e.*, the VEV of  $S$ , is  $\mathcal{O}(10^{-10} - 10^{-4})M_{\text{string}} = \mathcal{O}(10^8 - 10^{14})$  GeV.

Higher order (non-renormalizable) terms, which arise from exchanges of massive (of  $\mathcal{O}(M_{\text{plank}})$ ) particles of string theory, are also present in the potential for  $S$ . They are of the type  $S^{2K+4}/M_{\text{plank}}^{2K}$  ( $K \geq 1$ ) and could compete with the radiative corrections included in (8). Such terms determine the scale of symmetry breaking to be of the order of  $\mathcal{O}([M_Z M_{\text{plank}}^K]^{\frac{1}{K+1}})$ . For example, for  $K = 1$  the symmetry breaking scale is of the order  $10^{11}$  GeV.

In either case the  $Z'$  acquires mass of the order of the intermediate scale. On the other hand, it is straightforward to show that the mass of the physical Higgs boson associated with  $S$  is of the order of the soft supersymmetry breaking mass terms. The exotic matter to which  $S$  couples via the Yukawa couplings of magnitude  $\mathcal{H}$  acquires mass of order  $\mathcal{H}S$ , *i.e.*,

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<sup>6</sup> In general, one also has to ensure that the exotic particle content is compatible with the unification of the SM gauge coupling constants [22]. This imposes another stringent constraint on the allowed exotic particle content.

that of the intermediate scale. In the absence of the relevant Yukawa couplings, the exotic matter would have a mass set by supersymmetry breaking mass terms, and thus would be of the weak scale.

Again there are string models which illustrate such scenarios [15], with the appropriate SM singlet multiplets and the necessary couplings to the exotic particles to ensure the symmetry breaking scenario discussed above.

Even in the absence of a  $U(1)'$  gauge symmetry it is possible for SM singlet scalar fields to acquire negative mass-square values at low energies due to the radiative mechanism if they have sufficiently large Yukawa couplings to other fields. Such scalars generally will not have quartic terms in the potential, and thus they would acquire intermediate scale VEV's.

### C. Other Implications of $U(1)'$

Let us briefly comment on a few related topics.

We have seen that under a certain set of assumptions the VEV's of standard model scalars will typically be either at the electro-weak scale, or at an intermediate scale. Intermediate scales are of interest in implementing the seesaw model of neutrino mass. However, one may still need non-renormalizable terms in the potential to implement realistic neutrino mass scenarios [24]. Also, one promising scenario for baryogenesis [25] is that a large lepton asymmetry is generated by the decays of the heavy Majorana neutrino associated with the seesaw, and then converted to a baryon asymmetry during the electro-weak transition. Such scenarios, while very attractive, cannot occur if there is a  $U(1)'$  which is only broken at the electro-weak to TeV scale [26], unless, of course, the heavy Majorana neutrino is a  $U(1)'$  singlet.

We would also like to point out that the string models with an additional  $U(1)'$  yield a natural solution to the so called  $\mu$  problem [27]. Namely, the mass parameter  $\mu$ , parameterizing the mixing of the two SM Higgs doublets, should be of the order of the electro-weak scale to ensure a realistic mass spectrum in the MSSM. In string theory, at large energy scales the  $\mu$  parameter is either of  $\mathcal{O}(M_{string})$  or zero, thus causing the phenomenological  $\mu$  problem. If, in the models with an additional  $U(1)'$ , there is a coupling of the SM singlet(s)  $S$  to the two SM Higgs doublets and  $S$  acquires a non-zero VEV's of order 1 TeV, then such a term would provide an effective  $\mu$  term of the order of the electro-weak scale.

We emphasize that the radiative SSB scenarios discussed in this paper require the existence of sufficiently large Yukawa couplings to drive the mass square values of the SM singlet  $S$  negative. This is most easily implemented if there exists exotic matter which transforms non-trivially under the SM gauge group. The exotic matter will then acquire mass terms given by the relevant Yukawa coupling times the VEV of  $S$ , as well as contributions from supersymmetry breaking mass terms. Such exotic matter typically exists in string models. It is usually vector, *i.e.*, both the left and right chiral fields occur as  $SU(2)$  doublets, or both as  $SU(2)$  singlets. However, if it carries SM quantum numbers it can destroy the success of the gauge coupling unification [22]. Such effects largely cancel if the light exotic matter corresponds to complete  $SU(5)$  multiplets, but that is not typically expected in the types of semi-realistic models we are discussing. Preserving gauge unification without fine-tuning is a stringent constraint on string model building, with or without an additional  $U(1)'$ .

## IV. CONCLUSIONS

We have explored the possible scenarios for (non-anomalous)  $U(1)'$  symmetry breaking, as is expected for a class of string models with the standard model gauge group and additional  $U(1)$  gauge factors which survive into the low energy theory below  $M_{string}$ . Under the assumptions that the additional  $U(1)'$  symmetry is not broken by shadow sector effects and that the supersymmetry breaking scalar mass-square terms are positive, the breaking is necessarily radiative. This requires the existence of additional matter with large enough Yukawa coupling to the standard model singlets responsible for the  $U(1)'$  symmetry breaking. Then, within a particular model with definite supersymmetry breaking mass terms, the symmetry breaking pattern, the couplings and the masses of the new gauge bosons, and those of the accompanying exotic particles are calculable. In that sense the string models yield predictions for the new physics associated with the new gauge bosons.

It turns out that for the class of string models considered the mass of  $Z'$  is either of  $\mathcal{O}(M_Z)$  or the intermediate scale of order  $10^{8-14}$  GeV. However, in both cases the mass of the associated physical Higgs bosons is in the electro-weak region. Our major conclusion, therefore, is that a large class of string models considered here not only predict the existence of additional gauge bosons and exotic matter, but often imply that their masses should be in the electro-weak range. Many such models are already excluded by indirect or direct constraints on heavy  $Z'$  bosons, and the  $Z - Z'$  mixing is often too large, especially for lower values of  $M_{Z'}$ . The scenario in which  $M_{Z'}$  is in the electro-weak range allows, without excessive fine tuning of the supersymmetry breaking mass parameters, for predictions of  $M_{Z'}$  within experimental reach of present or future colliders. On the other hand, when the experimental bounds on  $M_{Z'}$  exceed the 1 TeV region, this scenario *cannot* be implemented without excessive fine tuning of supersymmetry breaking mass parameters, or unusual choices of  $U(1)'$  charge assignments.

String models provide a concrete set of predictions for new gauge boson physics, thus motivating the  $Z'$  searches and the associated exotic particle searches at future experiments, as perhaps the best motivated physics, next to that of the Higgs and supersymmetric partner searches.

## ACKNOWLEDGMENTS

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	$Z_\chi$	$Z_\psi$	$Z_\eta$	$Z_{LR}$	$Z''$
$\theta_{min}$	-0.0041	-0.0028	-0.0069	-0.0012	-0.0027
$\theta_{max}$	0.0011	0.0034	0.0020	0.0029	0.0004
$M_{Z'}$ (precision)	350	165	220	390	1000
$M_{Z'}$ (direct)	425	415	440	445	505

TABLE I. 95% CL lower limit on  $M_{Z'}$  in GeV and 95% CL upper and lower limits on the  $Z - Z'$  mixing angle  $\theta_{Z-Z'}$  for some common reference models, from precision data (updated from [1]) and direct searches [3,6]. Recent (preliminary) CDF data increase the direct  $Z''$  limit to 625 GeV.

## Appendix

As described in the Introduction, the experimental constraints on the  $Z - Z'$  mixing angle  $\theta_{Z-Z'}$  from precision (mainly  $Z$ -pole) data are stringent but very model dependent. It is common to quote limits on the masses and mixings of a heavy  $Z'$  with couplings given by a number of reference models. These include models based on grand unification: the  $Z_\chi$ , occurring in  $SO(10)$  models, and the  $Z_\psi$  and  $Z_\eta$ , which correspond to two patterns of  $E_6$  breaking. Other common reference models include the  $Z_{LR}$ , from left-right symmetric models, and the  $Z''$ , which has the same couplings as the  $Z$ . The latter would not occur in a realistic gauge theory, but is a convenient reference. The current 95% CL limits on the mass and mixing for each of these models are shown in the Table.

The limits in the Table assume that  $\theta_{Z-Z'}$  and  $M_{Z'}$  are independent parameters. However, in specific models these are related if one knows the  $U(1)'$  charges of the Higgs doublets which break  $SU(2)$  and generate the mixing. The relation is especially simple if only one  $SU(2)$  doublet is involved. Assuming  $M_{Z'} \gg M_Z$  the mixing angle and masses are related by (7). This relation is more general than the string or grand unified models considered here, and assumes only that there is a mass hierarchy and that the mixing is dominated by a single Higgs doublet. In the reference grand unified and left-right models one finds (assuming the simplest Higgs structure and direct breaking of the grand unified theory to the standard model with an additional  $U(1)$ ) that  $2g'|Q'_H|/G$  is in the range 0.2 – 0.6, so the mixing limits in the Table imply lower limits on  $M_{Z'}$  around 1 TeV. (In most cases the limits are relaxed when one allows two or more Higgs doublets to contribute, since their contributions can cancel in the off-diagonal term in the  $Z - Z'$  mass matrix.)

For such couplings, the mass hierarchies that can be generated without excessive fine tuning in the string models considered here would be inconsistent or only barely compatible with current experimental limits. However, the string-derived models are not expected to have precisely the same couplings and  $U(1)'$  charges as the models based on simple grand unification, and one could have smaller predicted mixings and/or less stringent experimental constraints.

For example, it is possible that a new  $Z'$  has suppressed couplings to charged leptons or to all ordinary fermions. Even if there are no selection rules to make the relevant charges vanish, one expects  $g'Q'$  to be small if the  $Z'$  couples to a large numbers of exotic particles. In a unified theory the overall strength of each gauge interaction, as normalized by  $g'^2 \sum_i Q_i'^2$ , should be the same or comparable. This implies that if a  $Z'$  couples to many particles, the

coupling to each particle individually is smaller, scaling roughly as  $1/\sqrt{N}$ , where  $N$  is the number of particles to which it couples. (This holds for the couplings at the string scale. It applies to the running couplings as well if the  $N$  particles are all light.) In particular, if  $g'Q'_H$  is small, then the predicted mixing is reduced. Similarly, small  $g'Q'_e$  leads to weaker experimental constraints on  $\theta_{Z-Z'}$ , since, roughly, the combination  $g'Q'_e\theta_{Z-Z'}$  enters most of the precision observables. (Of course, suppressed couplings would also make the discovery of a  $Z'$  in the future more difficult).

As an extreme model, one can consider a  $Z'$  that does not have any couplings to ordinary fermions. The  $Z - Z'$  mixing still affects the precision observables because it shifts the  $Z$  mass below the standard model expectation (see below). A global fit to all data gives the best fit at  $M_{Z'} = 130$  GeV, although the standard model ( $M_{Z'} = \infty$ ) is allowed at 90% CL, and  $\theta_{Z-Z'} = -0.05^{+0.03}_{-0.02}$ .

To understand this relaxed constraint better, it is convenient to consider the relation

$$\tan^2 \theta_{Z-Z'} = \frac{M_0^2 - M_Z^2}{M_{Z'}^2 - M_0^2} \quad (9)$$

between the mixing angle, the physical  $Z$  and  $Z'$  masses, and  $M_0$ , which is the the standard model prediction for the  $Z$  mass in the absence of mixing. This constraint holds in all models, even when the  $Z'$  coupling to the ordinary fermions is absent. Assuming  $M_Z \sim M_0$  and  $M_{Z'} \gg M_Z$ , this implies

$$|\theta_{Z-Z'}| \sim \frac{\sqrt{\rho_1 - 1}}{\sqrt{\rho_2^{-1} - 1}}, \quad (10)$$

where  $\rho_1 = M_0^2/M_Z^2$  and  $\rho_2 = M_0^2/M_{Z'}^2$ . The experimental error on  $M_Z$  is negligible. However, the standard model prediction for  $M_0$  is uncertain due to  $\sin^2 \theta_W$ ,  $m_t$ ,  $M_H$ , and  $\alpha(M_Z)$ , which altogether yield an uncertainty of  $\sim \pm 0.03$  in  $\sqrt{\rho_1 - 1}$ . This uncertainty is increased to  $\sim \pm 0.06$  if one allows modest couplings of the  $Z'$  to electrons, where we have assumed that such couplings can distort the apparent  $\sin^2 \theta_W$  obtained from  $Z$ -pole asymmetries by around 0.001. In Figure 3 we indicate the range of upper limits on  $\theta_{Z-Z'}$  allowed by (10) for  $\sqrt{\rho_1 - 1} = 0.03$  and 0.06 as a function of  $M_{Z'}/M_Z$ . This is the plausible experimental bound for models with suppressed  $Z'$  couplings to charged leptons.

The predicted mixing can be smaller than the grand unification values for small  $g'Q'_H$ . It can also be smaller when two or more Higgs doublets contribute significantly to the mixing, as is expected to be the case in both superstring models and supersymmetric grand unification (*i.e.*, away from the large  $\tan \beta$  limit). In this case, their contributions to the mixing can cancel. A plausible (but not rigorous) range for the effective value of  $2g'|Q'_H|/G$  is 0.5 to 0.1. This is also shown in Figure 3.

Thus, although many models are excluded by existing mixing constraints, there is a reasonable amount of allowed parameter space, certainly enough to motivate continued searches.



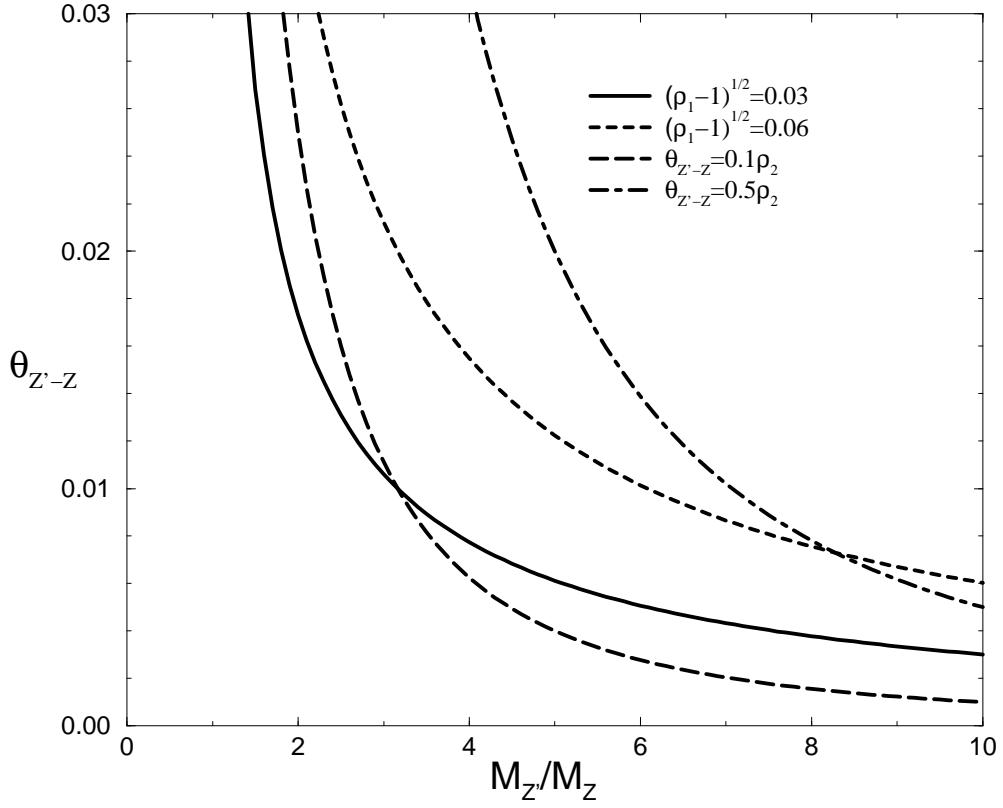


FIG. 3. Theoretical expectation for  $\theta_{Z-Z'}$  as a function of  $M_{Z'}/M_Z$  from (7) for  $2g'|Q'_H|/G = 0.5$  and  $0.1$ . Also shown are the upper limits on  $\theta$  implied by the shift in the  $Z$  from its standard model expectation (eqn (10)) for  $\sqrt{\rho_1 - 1} = 0.03$  (experimental  $\sin^2 \theta_W$  not affected by mixing), and  $0.06$  ( $\sin^2 \theta_W$  affected).